Appendix 7A

Review of Groundwater Modeling for Selected Aquifers Underlying the Longhorn Partners Pipeline, Prepared by R.J. Brandes Company

TECHNICAL MEMORANDUM

REVIEW OF GROUNDWATER MODELING FOR SELECTED AQUIFERS UNDERLYING THE LONGHORN PARTNERS PIPELINE

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1.0 EXECUTIVE SUMMARY

The Longhorn Partners Pipeline traverses Texas from Houston to El Paso. The pipeline, which is currently unused, was formerly used for transmission of crude oil and is now proposed to carry refined petroleum products such as gasoline and diesel fuel. The pipeline crosses the outcrop of many aquifers including the Edwards-Trinity (also known as the Edwards-Trinity Plateau), the Edwards (Barton Springs Segment), the Carrizo-Wilcox, the Colorado River Alluvium, and the Gulf Coast Aquifers. Concern has been raised regarding the possibility of groundwater contamination with refined products such as gasoline, including gasoline containing the additive MTBE (methyl tertiary butyl ether), and diesel fuel as a result of a pipeline leak or rupture. These products, particularly gasoline and MTBE, are potentially more mobile in groundwater than crude oil because they contain a higher percentage of water-soluble constituents.

The purpose of this Technical Memorandum is: 1) to review the literature to examine published numerical models of selected aquifers underlying the pipeline route and assess their applicability for spill characterization; and 2) to assess the potential impacts to the selected aquifers in the event of a pipeline leak or rupture. The following aquifers were selected for the assessment: the Edwards-Trinity, the Edwards (Barton Springs Segment), and the Carrizo-Wilcox. The following is a summary of the findings.

- No existing numerical model has all of the components necessary to characterize a pipeline leak. The available models reviewed in the study were all regional in scope. There is a general lack of data required to construct elaborate numerical models that could be used to evaluate a pipeline leak on a local scale. Therefore, analytical modeling techniques employing the best available data would provide the most useful results in cases where estimates of groundwater contaminant transport are required.

- Studies indicate that free phase and dissolved phase hydrocarbon plumes reach a steady state and do not expand significantly after an initial period, in shallow, unconsolidated aquifers composed of interbedded sands, silts, and clays (i.e. clastic materials).

  -- The main hydrocarbon constituents from gasoline (benzene, toluene, ethylbenzene, and xylenes, or BTEX) tend to move slower than the average groundwater flow rate when dissolved in groundwater. This is due to dispersion, dilution, sorption, and biogeochemical processes where native bacteria consume the hydrocarbons under aerobic and anaerobic conditions.

  -- The natural biodegradation of MTBE has not been completely documented in the literature, but it appears that degradation occurs very slowly compared to other fuel hydrocarbon constituents. MTBE is also more soluble than other constituents. MTBE, dissolved in groundwater, would tend to move at the average linear groundwater velocity and would be the fastest moving constituent. Dilution and dispersion would be the primary attenuation mechanisms for MTBE with distance from a spill.

- Tracking and remediating hydrocarbon plumes in karst aquifers such as the Edwards-Trinity and the Barton Springs Segment of the Edwards is more problematic than in shallow clastic aquifers (such as the Carrizo-Wilcox). This is due to the unpredictable distribution of fractures and secondary (solution) porosity features in hard rock.

- Based on the available information, the aquifers, in order of highest to lowest contamination potential, are: 1) Barton Springs Segment of the Edwards Aquifer, 2) Edwards-Trinity Aquifer, and 3) Carrizo-Wilcox Aquifer.

- Barton Springs Segment of the Edwards Aquifer is the most sensitive.

  -- Contributing Zone - The existing pipeline route crosses Barton Creek in the contributing zone of the aquifer approximately 3000 feet east of the Cedar Valley Pump Station. This would be a sensitive area, because in the event of a leak, contaminants could be washed downstream into the recharge zone.

  -- Recharge Zone - In the recharge zone, the existing pipeline does not cross any of the recharge-contributing creeks. However, beginning a short distance west of Brodie Lane and extending about one mile west, it does cross one of the most sensitive portions of the aquifer which is the outcrop of the permeable Kirschberg Evaporite member of the Kainer Formation and the leached and collapsed members of the Person Formation. The City of Austin has designated the Brodie Lane Karst Area as a Sensitive Karst Area because it contains a high concentration of karst features. The existing pipeline passes within 100 yards of the Brodie Lane Karst Area. This area is sensitive because runoff from an adjacent spill could enter the groundwater very quickly.

  -- Austin Re-Route Alternative - In the event of a spill impacting groundwater, this more southerly pipeline route would reduce the probability of contamination of Barton Springs. However, the majority of the groundwater produced for drinking water from the Barton Springs Segment is in the southernmost portion. Therefore, moving the pipeline to the south has the drawback of possibly contaminating drinking water supply wells downgradient of the pipeline in the event of a spill. The existing pipeline is primarily in the Slaughter Creek watershed, which contributes about 6% of the annual recharge to the aquifer. Moving the pipeline to the south would place it in the Bear and Little Bear Creek watershed, which contributes 14% of the annual recharge to the aquifer. The pipeline would directly cross Bear and Little Bear Creeks in the recharge zone making it the most sensitive portion of the pipeline route over the Edwards.

- The possible pipeline impacts on the Edwards-Trinity are of concern, but less than in the Balcones Fault Zone portion of the Edwards Aquifer.

  -- Groundwater flow rates in the Edwards-Trinity Aquifer are relatively slower than in the Balcones Fault zone portion of the Edwards Aquifer. Recharge rates are also lower in the Edwards-Trinity segment and the type of rapid flushing seen in the Balcones Fault Zone segment is less prevalent. However, there is uncertainty regarding groundwater flow in any fractured aquifer. The regional characteristics of the aquifer stated above do not preclude the possibility of rapid localized groundwater movement with unexpected linear direction. Also, the soil conditions on the Edwards Plateau are not favorable for natural biodegradation of spilled petroleum products over time. A spill on the Edwards Plateau is a critical issue because the groundwater is, in most cases, the sole reliable source of drinking water. Sensitive areas on the Edwards Plateau portion should include areas where drinking water wells are adjacent to the pipeline.

- The Carrizo-Wilcox is an unconsolidated clastic aquifer and is less likely to be contaminated over a large extent by a pipeline spill than the karstic aquifers to the west.

  -- Flow in the aquifer is laminar and much slower than in hard rock aquifers such as the Barton Springs Segment of the Edwards. Native bacteria will allow for natural biodegradation of most of the gasoline constituents. Another factor in the Carrizo-Wilcox is the aquifer's tendency to reject recharge. The aquifer is so "full" (water levels are high) that much of the water that is potential recharge is discharged to creeks. If a spill occurs near a waterway, and if a significant rainfall event has recently occurred, chances are good that either free phase or dissolved phase contaminants will be discharged to surface waters.

- Aquifer sensitive areas should include any segment where sole source drinking water wells are adjacent to the pipeline.

- To estimate the rate of movement of contaminants in groundwater resulting from a spill, a conservative assumption is that dissolved contaminants are estimated to move at the average linear groundwater velocity. Further, it is assumed that contaminants dissolve in groundwater immediately following a spill and are not retarded or degraded. Since these are average estimates, note that dissolved constituents could move faster or slower than the average rate.

  -- Edwards-Trinity Aquifer - Groundwater flow rates could range from 10 to 1230 feet per year. Dissolved contaminants such as MTBE and BTEX compounds could potentially migrate this far in one year following a spill.

  -- Edwards Aquifer Barton Springs Segment - From tracer studies, groundwater flow rates could range from 0.07 to 4.0 miles per day. Dissolved contaminants such as MTBE and BTEX compounds could potentially migrate this far in one day following a spill.

  -- Carrizo-Wilcox Aquifer- Groundwater flow rates could range from 10 to 2200 feet per year. Dissolved contaminants such as MTBE could potentially migrate this far in one year following a spill. BTEX compounds could move at these rates but would likely move slower.

2.0 INTRODUCTION

The purpose of this Technical Memorandum is to: 1) review the literature to examine published models of select aquifers underlying the pipeline route and assess their applicability for spill characterization; and 2) assess the potential impacts to the selected aquifers in the event of a pipeline leak or rupture. The study focus is on possible impacts to unconfined groundwater underlying recharge areas. The Longhorn Partners Pipeline traverses Texas and would transmit refined petroleum products from the Houston area to the El Paso area (Figure 1). The pipeline route traverses the surface expression (or outcrop) of sensitive groundwater-bearing geologic formations (aquifers) in populated and unpopulated areas. Concern has been raised regarding the proposed Longhorn Partners Pipeline operation because refined products such as gasoline, diesel fuel, and methyl tertiary butyl ether (MTBE, as a component of certain gasolines) would be transmitted. These products (particularly gasoline with MTBE) are potentially more mobile in groundwater than crude oil because they contain a higher percentage of water-soluble constituents. Two other existing pipelines, one carrying crude oil and one carrying liquefied petroleum gas, parallel the Longhorn Pipeline route.

Because of the length of the pipeline, it was necessary to scope the study to select the most sensitive and important aquifers that could potentially be impacted by a pipeline leak or rupture. The study focused on three aquifers that underlie the proposed pipeline route. From west to east they are the Edwards-Trinity Aquifer, the Barton Springs Segment of the Edwards Aquifer, and the Carrizo-Wilcox Aquifer.

Figure 1

3.0 MODELING COMPONENTS REQUIRED TO CHARACTERIZE A LEAK OR RUPTURE

From a modeling standpoint, several components are necessary in order to characterize a pipeline leak. These include:

- the spill volume;
- the impact pathways;
- the physical and hydraulic properties of the soil and aquifers, and;
- the chemical and physical properties of the contaminant.

The model selected for use must be appropriate for the application. Preferably, the model should be peer reviewed, published, and available to the public. This allows verification of the modeling results by interested parties. Codes should also be verified and tested against standard analytical solutions. An aquifer model should also be calibrated to available head, contaminant transport, and well test data.

Potential groundwater impacts in this study focus on semi-confined and unconfined (water table) aquifers in their surface outcrop (or recharge) areas. Impacts to downdip confined portions of aquifers are possible from contamination in recharge areas. However, confined portions of aquifers are typically miles downgradient with travel times measured in years from the recharge area. For this assessment study, the impacts to unconfined (or semi-confined) groundwater underlying a leaking or ruptured portion of the pipeline in the recharge area are considered to be more acute.

3.1 Properties of the Possible Contaminants

Gasoline containing up to 15% MTBE could be transmitted by the pipeline. Because it is refined, gasoline consists of a higher proportion of lighter organic constituents than those found in crude oil. Therefore, certain dissolved gasoline constituents can be more mobile in groundwater than can those in crude oil. Diesel is heavier has lower concentrations of light hydrocarbons than gasoline and would have a mobility in between that of gasoline and crude oil. Fuel hydrocarbons are less dense than water and will float on top of the water table in spill situations. Under normal conditions of standard temperature and pressure, gasoline and MTBE are liquids that are basically immiscible with water, although MTBE is considered partially soluble. When the gasoline/MTBE mixture comes into contact with groundwater, some fraction of the constituents can dissolve in the groundwater. It should be understood that the solubility of individual gasoline constituents in a mixture is less than the solubility of the pure substance in water (Larkin and Kent, 1990). For example, the total gasoline solubility in water is approximately 100 to 300 mg/L. This means that the solubility of individual constituents would be less than 100 to 300 mg/L from a gasoline spill.

Dissolved in groundwater, the major organic constituents of concern from gasoline would be the additive MTBE and the BTEX (benzene, toluene, ethylbenzene, and xylene) compounds. Diesel does not contain MTBE and contains much lower concentrations of BTEX than both gasoline and crude oil (Gustafson, et al., 1997). U. S. EPA Maximum Contaminant Levels (MCL) in groundwater for these constituents are: 0.005 mg/L benzene (carcinogen); 0.7 mg/L ethylbenzene (liver, kidney, nervous system effects); 1.0 mg/L toluene (liver, kidney, nervous system effects), 10.0 mg/L xylenes (liver, kidney, nervous system effects). Benzene is a known human carcinogen. There is no MCL for MTBE but a drinking water advisory level of 0.02 to 0.04 mg/L has been set. It is considered undesirable in drinking water because of its impact on taste and odor and because it has a low biodegradation potential. MTBE has a relatively low octanol-water partitioning coefficient (about 16) compared to fuel hydrocarbons, which means that it has a comparatively high solubility in water. Up to 250 mg/L has been measured in groundwater (Squillace et al., 1998; Landmeyer et al., 1998).

3.2 Possible Groundwater Impact Pathways

For the purposes of this study, a leak or rupture could occur at the surface or in the subsurface. The pipeline is buried for most of its length and is above ground in some places including some stream crossings. The typical depth of burial varies from approximately two to six feet with native material commonly used as backfill. In areas having a thin soil, this backfill could consist of a mixture of soil and excavated rock.

3.2.1 Description of Possible Pipeline Leak Impacts

A leak could result in a slow, steady source of contamination at the surface or in the subsurface. Pure product could slowly infiltrate through the soil and eventually reach the water table (Figure 2). Once at the water table, it would float as a separate phase if the volume of the leak is large enough (both MTBE and gasoline are less dense than water). A dissolved phase plume of organic constituents would result from groundwater contact with the product. When free phase hydrocarbons float on the water table, a smear zone tends to form in the vadose zone and capillary fringe area as a result of natural fluctuations in water levels. This complicates remediation efforts because the smear zone creates a reservoir of contamination that can continue to provide a source even after free phase is removed.

Product and contaminated groundwater would move at different rates. Dissolved phase plumes typically travel faster and farther than pure product. Free phase plumes are usually confined to the area adjacent to the spill but can cover larger areas if the volume is large enough. Large free phase plumes floating on the water table have been detected underlying several chemical plants and refineries in Texas. In these situations, the free phase plumes have developed over many years and involve millions of gallons of product.

If the volume of the spill is small, pure product will remain “trapped” in the unsaturated zone above the water table (Figure 3). Contamination of groundwater could

Figure 2

Figure 3

also occur as a result of product dissolving into infiltrating recharge water. The contaminated recharge would eventually reach the water table and impact groundwater as a dissolved phase plume that would move in the downgradient direction.

3.2.2 Description of Possible Pipeline Rupture Impacts

Operating pressures for the pipeline are expected to range from 600 to 900 psig. Depending on its orientation on the pipe, depth of cover and other factors, a leak (or catastrophic pipe failure) could result in any or a combination of the following: 1) a blowout of surface materials followed by pooling of product on the surface and subsequent infiltration through soil, 2) injection of product under pressure in the subsurface, 3) both 1 and 2, or 4) runoff of pure product. The following case studies illustrate the fate of hydrocarbons spilled from pipeline breaks over thick soils. In these cases, remedial actions or no action alternatives proved to be adequate. The fate of hydrocarbons over hard rock aquifers with thin overlying soils may be different.

In 1988, a buried pipeline ruptured at Kelly Air Force Base in Texas resulting in a release of approximately 80,000 gallons of JP-4 jet fuel (Larkin et al., 1991). The fuel ponded in a depression on the surface with an estimated radius of 60 feet. Within 45 minutes the fuel had infiltrated through low permeability terrace deposits and reached the water table 26 feet below the surface. It is assumed that fractures and macropores in the clay rich soil allowed for the rapid infiltration. Two thousand gallons of free phase JP-4 were recovered from the surface of the water table over a two-year period. Soil borings confirmed that most of the fuel remained trapped in the vadose zone within a 60 feet radius of the spill. A pilot test proved the feasibility of removing trapped hydrocarbons with soil vapor extraction (SVE). The removal of 286 pounds per day of the volatile fraction of the JP-4 was achieved. A full scale SVE remediation system was constructed (Coho and Larkin, 1992) and volatile vapor removal was initially 29 pounds per hour. This decreased to 12 pounds per hour by day 60. Clear evidence of biodegradation of the non-volatile fraction of JP-4 was determined from a respiration test. The final remediation consists of a passive system designed to aerate the subsurface and allow for natural attenuation of the remaining JP-4.

Surface spraying of oil and subsequent pooling and infiltration through the vadose soon was reported by Essaid et al. (1994) from a pipeline leak in Minnesota. Approximately 460,000 gallons of oil were spilled. Crude oil was sprayed over a radius of about 140 feet causing pooling on the surface and subsequent infiltration into the subsurface forming bodies of oil that floated on the water table. It is estimated that 70% of the oil was recovered on the surface. The rest infiltrated through approximately 20 feet of glacial till to reach the water table.

Several studies have shown that free phase and dissolved phase hydrocarbon plumes reach a steady state and do not expand significantly after an initial period. Baedecker et al. (1996) found that after the Minnesota crude oil pipeline rupture discussed above, a resulting groundwater plume moved only 450 feet downgradient of the oil body. The BTEX hydrocarbon constituents tend to move slower than the average rate when dissolved in groundwater. This is due to dilution, dispersion, sorption, and biogeochemical processes where native bacteria consume the hydrocarbons under aerobic and anaerobic conditions. After the spill, oxygen has been consumed in the center of the plume, and anaerobic bacterial degradation continues to occur because organisms obtain oxygen from the reduction of methane and iron. At the fringes of the plume, dissolved oxygen in the groundwater supports aerobic degradation of the hydrocarbons into CO_2 and water. From an underground storage tank leak, Fischer et al. (1996) determined that dissolved concentrations in a gasoline plume decreased with time. This was attributed to natural attenuation. Mace et al. (1997) studied information from 605 leaking petroleum storage tanks in Texas. They concluded that, even without remediation, plume mass and length increases, stabilizes, and then rapidly declines over time. Only 14% of the benzene plumes studies were increasing in concentration and 3% were increasing in length. This was also attributed to natural attenuation, including bioremediation and volatilization.

The natural degradation of MTBE has not been completely documented in the literature. It does appear that some natural degradation of MTBE does occur (Stocking et al., 1999), although it is likely that degradation occurs very slowly compared to other fuel hydrocarbon constituents. Landmeyer et al. (1998) reported low but recordable biodegradation potential in laboratory studies. Although biodegradation has been observed with pure MTBE, or with MTBE as a component, there are problems. First, microbial mass seems to be low and the reason is not clearly understood. Also, the presence of more easily degraded hydrocarbons may inhibit MTBE degradation. Natural attenuation of MTBE could likely be enhanced by the introduction of oxygen in the subsurface. MTBE would travel at the advective groundwater flow rate if a pipeline leak or rupture resulted in dissolved gasoline constituents in groundwater (Landmeyer et al., 1998). In any event, dispersion and dilution will act on dissolved constituents (including MTBE) to reduce contaminant concentrations downgradient of the spill site (Landmeyer et al., 1998). A plume of MTBE from a leaking storage tank was reported to have migrated 750 feet from the source area in 10 years (Landmeyer et al., 1998).

3.3 General Aquifer Impact Sensitivity to a Pipeline Spill

Several considerations are important in judging the relative sensitivity of an aquifer to a pipeline spill. Aquifer sensitive areas should include any segment where sole source drinking water wells are adjacent to the pipeline. The soil type overlying the aquifer and the type of flow regime in the aquifer will have an impact on how quickly contaminants can reach the water table and then be transported. In general, contamination from refined petroleum products is less of a concern when thick, organic-rich soils are present. In this situation, naturally occurring bacteria that consume hydrocarbons are often plentiful. Also, hydrocarbons sorb onto organic carbon resulting in a retardation of their movement relative to the native groundwater velocity. It should be recalled that MTBE has a lower potential for biodegradation than other petroleum hydrocarbons.

Regarding aquifer type, unconfined aquifers in areas of focused recharge are more likely to be impacted from a pipeline spill than confined aquifers. Contamination from hydrocarbons is more of a concern in hard rock aquifers such as the Edwards-Trinity and the Barton Springs segment of the Edwards Aquifer. Because recharge can enter these aquifers quickly, gasoline could also infiltrate rapidly from a surface spill. Saturated flow rates and direction in these fractured and cavernous limestones can be rapid and hard to predict. Contributing to all this is the fact that soils are basic and generally thin and poorly developed over the Edwards.

Contamination of the Colorado River Alluvium would also be problematic because of the hydraulic connection between surface water and groundwater. A pipeline break over the alluvium would probably quickly infiltrate and seep into the Colorado River.

Contamination from a pipeline spill would be less of a concern in unconsolidated clastic aquifers such as the Gulf Coast Aquifer and the Carrizo-Wilcox. Groundwater flow rates are generally slower in these aquifers, and the flow direction is better defined. Soils are thick and well developed, providing a ready source of native bacteria.

3.4 Unsaturated Zone Model Considerations and Impacts

If a pipeline failure occurs on the soil surface, the contaminant must first travel through the unsaturated zone before reaching the water table. Only when pure product or dissolved constituents reach the capillary fringe just above the water table can organic constituents enter the groundwater. Depending on the conditions, the product could pool on the surface and slowly infiltrate through the soil or it could travel quickly to groundwater. For example, over the Barton Springs segment of the Edwards Aquifer, a surface spill could be transmitted quickly to groundwater due to the fractured and karstified nature of the recharge zone. Likewise, a rapid impact could occur from a surface leak overlying the Colorado River Alluvium. This aquifer is very permeable and is in hydraulic communication with the Colorado River.

Assuming pooling over a soil horizon, numerical models of unsaturated flow must be capable of modeling the movement of three phases: air, water, and an immiscible oil phase. Existing numerical models are very complex and the data required to run them are often non-existent. Commonly, so many assumptions must be made that it renders the results to be of questionable validity. The best approach is to use analytical calculations or a computer implemented analytical scheme such as the Regulatory and Investigative Treatment Zone Model (RITZ, Nofziger et al., 1988) or the Hydrocarbon Spill Screening Model (HSSM, Weaver et al., 1994) to estimate the vadose zone travel time. Even then, a significant number of assumptions and simplifications regarding model inputs must be made. For example, these approaches usually assume homogenous conditions, one-dimensional (vertical) flow and ignore capillarity and hysteresis in the unsaturated zone.

To determine the travel time through the unsaturated zone, it is necessary to know its thickness, the volume of the leak, the surface area over which a spill occurred, the moisture content of the soil, the type of soil, and the composition of the contaminants. Then, an estimation can be made if product will reach the water table.

The movement of free phase hydrocarbon floating above the water table is very difficult to model for the same reasons mentioned above for vadose zone transport. Capillarity is difficult to model accurately, and multiphase flow must be modeled in a situation where virtually all the model inputs must be assumed. Again, the best approach is to use analytical schemes that impose simplifications rendering the results suitable for the screening process. HSSM (Weaver et al., 1994) is a U. S. EPA model that contains a free phase oil lens movement component.

3.5 Saturated Zone Model Considerations and Impacts

The worst case scenario for a subsurface leak or rupture would be a direct impact of pure product to the water table. Models of contaminant transport in groundwater from pipeline leaks are complicated by the possible presence of a less dense hydrocarbon phase that will float on the water table because the product is immiscible in water. If product reaches the water table, it will act as a source and continue to contribute dissolved organic constituents the groundwater. If the volume of the spill is too low, or the spill area is very broad, product will not reach the water table. In this case, only dissolved constituents will enter the groundwater via the vadose zone.

4.0 EDWARDS-TRINITY AQUIFER - HYDROGEOLOGY AND REVIEW OF EXISTING MODELS

The existing Longhorn Pipeline traverses central Texas, and the underlying Edwards-Trinity Aquifer (Figure 4). The counties traversed by the pipeline in the Edwards-Trinity Aquifer region are Kimble, Menard, Schleicher, Crockett, Reagan, and Upton. Information has also been obtained related to the hydrogeologic characteristics and hydraulic parameters that could be used in future modeling.

4.1 Hydrogeology of the Edwards-Trinity Aquifer

The Edwards-Trinity Aquifer consists of the rocks from the base of the Antlers Formation (Trinity Group) to the top of the Georgetown Formation (top of the Edwards and associated limestones). Rocks in the Antlers are sands and limestones. The water-bearing sands contain mainly primary porosity but may contain secondary porosity if evaporites are present. Rocks in the Edwards are limestones containing secondary porosity due to dolomitization and solution porosity caused by groundwater flow. Recharge is by precipitation on the outcrop. There is no discussion in the literature regarding possible focused recharge.

On the eastern and southeastern edge of the plateau, the saturated thickness of the Edwards-Trinity Aquifer is thin and groundwater discharge is rapid through seeps and springs. Regionally, the Antlers Formation and the Edwards and associated limestones are considered to form one aquifer. In some areas, however, freshwater is confined to the Antlers. Freshwater is located below the Edwards limestones in parts of Upton and Reagan Counties. In parts of Crockett and Reagan Counties, the Santa Rosa Formation is included in the Antlers. The pipeline route traverses Reagan County near the town of Big Lake. In this area the aquifer attains its greatest saturated thickness of approximately 700 feet (Walker, 1979).

Figure 4

From well tests, the average transmissivity for the Antlers (Trinity) Aquifer is 365 ft^2/day. The storativity for the Antlers is 0.074 and the hydraulic conductivity ranges from 1.7 to 5.1 feet/day. The storativity of 0.074 is a typical value for an unconfined aquifer. The storativity and the hydraulic conductivity of Edwards and associated limestones from well tests are not available.

Both confined and unconfined conditions occur. Depth to groundwater varies, as the Edwards can be dry in some cases. This means that the top of groundwater is in the Trinity in some locations. Information regarding interformational flow is not available. Natural discharge occurs in springs and seeps along the borders of the plateau where erosion has cut streams down to the depth of the water table. In cases where the water levels in wells are above the top of the Antlers, the Edwards and the Antlers are considered to be one aquifer.

The hydraulic gradient on the Edwards Plateau ranges from 5 to 50 feet per mile. Typically, the rate of groundwater movement in the Antlers ranges from a few feet to several feet per year (Walker, 1979). Figure 5 is a potentiometric surface map for the Edwards-Trinity Aquifer. However, groundwater moving through fractured, jointed, or solutioned rocks could move on the order of several hundred feet per day (Walker, 1979). Saturated thickness generally increases from southeast to northwest along the route of the pipeline (Table 1). Water level declines have been reported over time as increasing demand places a greater demand on available resources. The depth to groundwater is estimated to be 100 to 200 feet below ground surface in the area traversed by the pipeline.

Although the rates of flow are lower than in the Balcones Fault Zone, large volumes of recharge move to the south and discharge to large springs such as Las Moras and San Felipe Springs. These discharge points are remote from the pipeline route and the chance is small that contamination from a spill would impact these springs. There are

Figure 5

Table 1. Approximate Edwards-Trinity Aquifer Saturated Thickness and Water Usage

County	Average Well Yield (gpm); Specific Capacity (gpm/ft)	Total Estimated Pumpage* (million gal/day)	Surface Water Usage (million gal/day)	Edwards-Trinity Aquifer Saturated Thickness (approximate)
Kimble	NA	0.88	4.68	100 feet average
Menard	NA	0.41	2.03	50 feet average
Schleicher	355; 4.4	2.29	0.13	100 to 300 feet
Crockett	242; 9.56	5.61	0.15	250 average
Reagan	89; 1.17	22.63	0.03	200 to 400 feet average 700 feet S. of Big Lake
Upton	172; 0.94	11.12	0.02	100 feet average

Source: Walker 1979 unless noted. NA = not available.

*Lurry and Barber (1990)

known cells of large groundwater capacity in the southern edge of the Edwards Plateau that appear to be fault bounded.

The chemical quality of the groundwater in the Edwards and associated limestones is very hard and has a range of 200 to 400 mg/L total dissolved solids (TDS). Antlers groundwater is also very hard and has an average total dissolved solids content of 530 mg/L. The total dissolved solids concentration generally increases to the west along the pipeline route (Bush et al, 1994). Groundwater generally has 150 to 500 mg/L TDS in Menard, Kimble, Crockett, and Schleicher Counties. Groundwater in Reagan and Upton Counties contains 1000 to 3000 ppm TDS.

4.2 Groundwater Models of the Edwards-Trinity Aquifer

There was only one existing model of the Edwards-Trinity (Plateau) Aquifer found during this study. Kuniansky and Holligan (1994) developed a steady state finite element model of the Edwards-Trinity Aquifer as part of the U. S. Geological Survey Regional Aquifer-Systems analysis program. This was accomplished by using a simplified, one layer, porous medium model. The mathematical model was developed especially for the study and is documented in Kuniansky (1990).

The model simulates groundwater flow only and assumes that flow in the aquifer is confined and laminar. This means that the model may not be appropriate in regions were turbulent flow or unconfined conditions may prevail. However, for much of the Edwards-Trinity Aquifer, the approximation of confined laminar flow is appropriate if modeled drawdowns are small compared to the total saturated thickness and the proper specific yield is used in the model. The laminar flow condition may not be met in recharge and discharge areas.

The model covers the entire area of the pipeline route overlying the Edwards-Trinity Aquifer. The first simulation period was for the winter of 1974-75. This time was chosen because a good set of measured head data was available for the period. Predevelopment conditions were then simulated to obtain a hydraulic head match.

The model was calibrated to observed historical water levels by adjusting the model inputs (transmissivity and leakage coefficient) and the model stresses (recharge and discharge) until a good fit was obtained with the simulated water levels. Flow was modeled to be isotropic in the Edwards Plateau. Transmissivity values used in the model simulations ranged from 2,500 to 5,000 ft^2/day in the portion of the model covering the pipeline route. From the simulations, the areally distributed recharge was estimated to be between 0.1 and 1.0 inch per year. Recharge volumes were estimated from base flow from streams traversing the Hill Country. Discharge was averaged over some elements and subtracted from the recharge.

The model simulated movement of water from the Edwards-Trinity Aquifer into the Balcones Fault Zone portion of the aquifer. This was simulated to be about 400 ft^3/sec of groundwater entering the Edwards Aquifer from the Edwards-Trinity Aquifer. An acceptable match was obtained to measured hydraulic heads according to the authors. However, the root mean square water level error was 83 feet for 259 observations in the Edwards Plateau. This means that there was a significant difference between simulated and measured heads in some parts of the model. From the model results, groundwater flow directions tended to be toward perennial streams and major springs.

4.3 Groundwater Impacts to the Edwards-Trinity Aquifer from a Pipeline Leak or Rupture

The possible pipeline impacts on the Edwards-Trinity are of concern, but less than in the Balcones Fault Zone portion of the Edwards Aquifer. Groundwater flow rates in the Edwards-Trinity Aquifer are relatively slower than in the Balcones Fault zone portion of the Edwards Aquifer. Recharge is by precipitation on the outcrop and is therefore, less focused than on the Balcones Fault Zone portion. Recharge rates are also lower in the

Edwards-Trinity segment and the type of rapid flushing seen in the Balcones Fault Zone segment is less prevalent. Groundwater flow in the plateau portion generally follows the slope of the topography with discharge to springs and seeps in the incised stream and river beds near the edge of the plateau.

However, there is uncertainty regarding groundwater flow in any fractured aquifer. The Edwards-Trinity Aquifer consists of fractured limestone and dolomite with caverns and other solution features in the subsurface. The regional characteristics of the aquifer stated above do not preclude the possibility of rapid localized groundwater movement with unexpected linear direction. In the event of a spill this could result in unanticipated movement of contaminants.

Another issue is related to the lack of a well-developed soil layer on the outcrop of the Edwards-Trinity Aquifer. Soils with a high fraction of organic carbon tend to sorb organic constituents and retard their movement in the unsaturated and saturated zones. Also, well-developed soils usually contain abundant native bacteria that consume the constituents in oil, diesel, gasoline, and other hydrocarbons rendering CO_2 and water over time. The soil conditions on the plateau are not favorable for natural biodegradation of spilled petroleum products over time.

Significant quantities of groundwater are used for domestic, agricultural and municipal use in the counties crossed by the pipeline route. This makes a spill a more critical issue because the groundwater is, in most cases, the sole reliable source of drinking water.

4.4 Modeling Groundwater Impacts to the Edwards-Trinity Aquifer from a Pipeline Leak or Rupture

Rose (1986) assessed pipeline leak statistics for the period 1971-1985 for the Edwards-Trinity Aquifer. There were 15,000 reported spills during the study period; 3

percent were spills of 42,000 gallons or more. Rose (1986) estimated that a spill of 42,000 gallons or larger has a reasonable probability of reaching the water table in the unconfined Edwards-Trinity. A spill of 210,000 gallons or greater was expected to result in groundwater contamination. On the average, 50 percent of spilled oil was recovered. A spill of such a magnitude is expected once every 15 months on average. This information could be used in modeling analyses as a basis for model volumetric input.

Based on the general direction of advective groundwater flow, dissolved contaminants would be expected to move in a south to southeasterly direction depending on the location. The exception could be near pumping centers where gradients could be reversed and dissolved contaminants could be drawn toward pumping wells. From Figure 5, advective transport would occur perpendicular to the potentiometric surface lines in the direction of decreasing hydraulic head.

The model of Kuniansky and Holligan (1994) provides results for groundwater flow but does not include contaminant transport. The model could be used as a tool to delineate regional advective movement of conservative dissolved contaminants in groundwater. It would be useful in simulations to determine rates of advective discharge to rivers and creeks.

One problem that is inherent in Edwards-Trinity (and Edwards Aquifer) models is the use of porous medium models to simulate fractured flow. This is less of a limitation in regional scale models (tens or hundreds of miles) that average groundwater flow over a county or counties. However, the use of a porous medium model to simulate cavernous or linear flow on a local scale is more problematic. Anisotropy and regions of differential transmissivity can be used regionally to calibrate regional porous medium models of groundwater flow. Contaminant transport models are more difficult to calibrate because of the general lack of data. Insufficient data regarding the nature of the subsurface at a local scale (less than one or two miles) makes it extremely difficult to reliably account for the possible existence of highly transmissive features such as joints, faults, or caverns that could invalidate the model predictions.

Consequently, the Kuniansky and Holligan (1994) model would not be appropriate for use on a local scale (less than one or two miles for example) because of the coarseness of the model grid. The model could not be used to model free phase product movement, unsaturated flow, or dispersive and diffusive movement of dissolved organic constituents. It is unknown whether this model has the ability to simulate retardation effects.

4.5 Estimates of Groundwater Velocity in the Edwards-Trinity Aquifer

A conservative approach for estimating contaminant transport velocities in groundwater is to assume that dissolved constituents move as conservative species that are not retarded or degraded in any way. Average groundwater flow velocities can then be assumed to be the rate of contaminant transport. In the Edwards-Trinity, the average groundwater flow velocities are on the order of a few feet per year

There are two sources of data for estimating the velocity in the Edwards-Trinity. The first is hydraulic conductivity and specific yield calculated from pumping test data. The second is the values used by Kuniansky and Holligan as a result of their model calibration. A range of velocities can be calculated from these two sources as shown below.

Using pumping test data for the Trinity Group (Antlers) and Darcy's law, the average groundwater velocity v is estimated as follows:

$$v = Q/An = Ki/n = 0.02 \text{ to } 0.69 \text{ feet/day} = 7.0 \text{ to } 252 \text{ feet/year}$$

Where:

Q = Volumetric Flow Rate

A = Area perpendicular to flow

n = Porosity ≈ specific yield = 7.4% (from pumping tests)

K = Hydraulic Conductivity = 1.7 to 5.1 feet/day (from pumping tests)

i = Hydraulic Gradient = 5 to 50 feet/mile ≈ 0.001 to 0.01

Using Kuniansky and Holligan (1994)'s calibrated model of the Edwards-Trinity Aquifer, values for transmissivity ranged from 2,500 to 5,000 ft^2/day. Assuming an average saturated thickness of 200 feet yields:

$$v = Ki/n = T/h/n = 0.16 \text{ to } 3.38 \text{ feet/day} = 58 \text{ to } 1234 \text{ feet/year}$$

Where:

T = Transmissivity = 2500 to 5000 $feet^2$/day (model calibration values)

h = Saturated Thickness = 200 feet (assumed)

K = T/h = Hydraulic Conductivity = 12.5 to 25.0 feet/day

n = Porosity ≈ specific yield = 7.4% (from pumping tests)

The problem with this approach is that, locally, groundwater flow rates could be much higher than the average because of fracturing or solutioning. Therefore, groundwater moving through fractured, jointed, or solutioned rocks could move on the order of several hundred feet per day (Walker, 1979).

5.0 BARTON SPRINGS SEGMENT OF THE EDWARDS AQUIFER - HYDROGEOLOGY AND REVIEW OF EXISTING MODELS

The current pipeline route crosses the contributing zone, the recharge zone, and the artesian portion of the Barton Springs Segment of the Edwards Aquifer. The current crossing is in south Austin roughly paralleling Slaughter Lane. The Austin Re-route Alternative would take the pipeline further south into northern Hays County through a less densely populated area. The aquifer provided drinking water to 44,000 people in 1995 (Hauwert et al., 1998).

5.1 Hydrogeologic Overview of the Barton Springs Segment of the Edwards Aquifer

This section presents a brief introduction to the hydrogeology of the Barton Springs Segment of the Edwards Aquifer. The Edwards Aquifer in this portion is a complex hydrogeologic flow system about which little is known with certainty. For example, adjacent wells can have yields that vary by four orders of magnitude (Slade et al., 1986.)

The Barton Springs segment of the Edwards Aquifer extends from a groundwater divide in northern Hays County to natural discharge points near Austin (Figure 6). The divide separates groundwater flowing south toward San Antonio from that flowing north toward the major discharge points of Barton Springs (97% of discharge) and Cold Springs and Deep Eddy Springs (3% of discharge). Cold Springs and Deep Eddy Springs are hydraulically separate and discharge from a different segment of the aquifer. Slade et al., (1986) report that, on average, these springs supply more than 50 ft^3/sec of fresh water to Town Lake. Buckner et al. (1989) report that the average discharge of Barton Springs is 56 ft^3/sec.

Figure 6

The Edwards Aquifer consists of the karstified Edwards Group of limestones and the overlying Georgetown Formation. With decreasing depth, the component formations of the Edwards Group are the Kainer, the Person and the Edwards (Senger and Kreitler, 1984). The most permeable member is the Kirschberg Evaporite member of the Kainer Formation and the leached and collapsed members of the Person Formation (Small et al., 1996). The overlying Georgetown Formation is usually considered to be part of the Edwards Aquifer because it is hydraulically connected to the Edwards Formation. The Edwards Aquifer limestones are confined by the Del Rio Clay, which overlies the Georgetown Formation. The Edwards and associated limestones consist of cherty, nodular, thin to massive bedded, white to gray limestone and dolomite that is characterized by fractures, joints, and extensive cavernous and vugular strata (Mace et al., 1997).

The Barton Springs Segment of the Edwards Aquifer is located in the Balcones Fault Zone. This is a northeast trending zone of en echelon (parallel) faults with as much as 400 feet of throw in the Austin area (Figure 7). These faults and secondary porosity features dominate the groundwater flow regime in the Edwards. Groundwater is unconfined in the outcrop (recharge) portion and confined where the Edwards is not exposed. Groundwater flow is strongly anisotropic. In the outcrop portion, large quantities of groundwater move to the east. Flow is then diverted to the north in the confined portion following the trend of the Balcones Fault Zone (Figure 8). The hydraulic gradient in the confined zone where flow is focused to the north is about 0.0024. The hydraulic gradient in the outcrop area where flow is directed to the east is approximately 0.014. Water levels in the confined portion are correlated with each other and with flow at Barton Springs (Slade et al., 1986). Water levels in the western outcrop portion change the least with low to high flow conditions (Barrett and Charbeneau, 1996).

Compared to aquifers composed of sand and silt, which have primary porosity, groundwater flow is relatively rapid through the Edwards Aquifer. This is due to the solutioning action of groundwater, which causes secondary porosity to dominate.

Figure 7

Figure 8

Secondary porosity features include sinkholes, caverns, and enlarged joints and fractures that are interconnected in the subsurface. The aquifer contains a well-developed system of conduits as evidenced by rapid increases in flow at Barton Springs following rains. The depth to groundwater in the area of the Edwards outcrop crossed by the pipeline is approximately 200 feet. The downdip extent of fresh water is delineated by the Bad Water Line. This roughly parallels the location of Interstate 35 and marks the beginning of groundwater with greater than 1000 mg/L TDS.

Recharge to the Edwards Aquifer is mainly by infiltration of streamflow through fractures and sinkholes in the creek beds crossing the Edwards outcrop. In the Barton Springs segment, this includes Onion Creek (46% of average annual creek recharge), Barton Creek (31% of average annual creek recharge), Williamson Creek (3% of average annual creek recharge), Slaughter Creek (6% of average annual creek recharge), Bear Creek, and Little Bear Creek (14% of average annual creek recharge) (Barrett and Charbeneau, 1996). Many streams are diverted completely underground during periods of low flow. The existing pipeline crosses primarily the Slaughter Creek watershed in the recharge zone. The Austin re-route alternative route would cross primarily the Bear and Little Bear Creek watershed. Some recharge also occurs from direct infiltration of precipitation on the outcrop particularly through sinkholes, faults, fractures, and solution cavities, which can rapidly transmit water to the aquifer.

From a hydrogeologic standpoint, the Edwards Aquifer can be divided into three portions: the contributing zone, the recharge zone, and the artesian zone. The contributing zone is that portion that is west updip of the Barton Springs Segment on the outcrop of the Glen Rose Limestone. Creeks crossing the Glen Rose outcrop contribute flow that eventually recharges the Edwards when the flow reaches the recharge zone. The recharge zone is located on the outcrop of the Edwards. The artesian zone is the downdip portion of the Edwards that is confined.

5.2 Groundwater Models of the Edwards Aquifer

Models of the Edwards Aquifer in the Barton Creek Segment include distributed parameter (finite difference and finite element) models and lumped parameter models. All of the models suffer from the lack of accurate input data.

5.2.1 Kuniansky and Holligan (1994)

Kuniansky and Holligan (1994) developed a steady state finite element model of the Edwards-Trinity and Edwards Balcones Fault Zone Aquifers as part of the U. S. Geological Survey Regional Aquifer-Systems analysis program. This was accomplished by using a simplified, one layer porous medium model. The model covers the entire area of the proposed pipeline route overlying the Barton Springs Segment of the Edwards Aquifer.

The model was calibrated to observed historical water levels by adjusting the model inputs (transmissivity, leakage coefficient, and anisotropy ratio) and the model stresses (recharge and discharge) until a good fit was obtained with the simulated water levels. However, the authors noted that there was more uncertainty to the calibrated values in the Balcones Fault Zone portion of the model. This was because of the model's relative insensitivity to changes in the input parameters. In order to account for faulting in the Balcones Fault Zone portion of the model, groundwater flow was modeled to be anisotropic with an anisotropy ratio of about 5 to 1. This means that the transmissivity in the direction parallel to the strike of the faults was greater by a factor of five than the transmissivity in the direction perpendicular to the faults.

Kuniansky and Holligan used a hydraulic conductivity range of 100,000 to over 1,000,000 feet/day in simulations of groundwater flow in the Edwards Aquifer. Specific yield in the unconfined portion of the aquifer in the Balcones Fault Zone was 0.03 and the storativity in the confined zone was 1×10^{-5} to 1×10^{-4}.

5.2.2 Barrett and Charbeneau (1996)

Barrett and Charbeneau (1996) developed a lumped parameter model to simulate flow and transport in the Edwards. The model was used to predict the impacts of urban development on the Barton Springs Segment of the Edwards Aquifer. The model consisted of five cells that represented conditions in five creeks contributing recharge to the aquifer. The cells were completely mixed tanks and each contained one well selected to represent conditions in the segment of the aquifer. The model was able to simulate measured water levels and nitrogen concentrations at Barton Springs for the period 1979 to 1995. The model results indicate that continued urban development will reduce average spring flow and will cause an increase in the average nitrogen concentration in the aquifer. The model does not include that portion of the aquifer that discharges to Cold Springs and Deep Eddy Springs. Flow between the cells was described using Darcy's Law.

The model was calibrated by comparing measured and predicted spring discharge and water levels during the recession period in the fall of 1989. A good match was obtained to the observed data. The flow model was verified by comparing measured and predicted spring discharge during the period 1979 through 1989. Predicted discharge typically exceeded the measured discharge. A sensitivity analysis was performed for the model inputs and the numerical accuracy and stability were tested with an integration technique and found to be satisfactory. As a test, a 50-cfs pulse of recharge was simulated in the Onion Creek cell. The pulse took 20 days to be detected in the Barton cell.

In the water quality assessment, the authors found that the water quality of Barton Springs has remained unchanged in the past 15 years. Only total nitrogen displayed any significant variation, which appears to be related to leaking sewers in 1982. Most of the variability in water quality changes at Barton Springs is restricted to the beginning of recharge events. Intense development (similar to that in the Shoal Creek watershed) was predicted to increase the total nitrogen concentration at Barton Springs from 1.5 to 3.5 mg/L. Another pulse-input simulation was performed using a hypothetical concentration of nitrogen of 129 mg/L to the Onion Creek cell. To make the simulation worst case, this was input on the day that a maximum recharge rate of 120 cfs was occurring in the creek. Concentrations in the ppb level were observed in the model Barton cell after 65 days. This did not include dispersion although subsequent simulations including dispersion showed little difference in the modeled concentrations.

5.2.3 RMT/Jones and Neuse (1994)

This modeling study was commissioned by the City of Austin Environmental and Conservation Services Department but has not been published in the open literature. Two scenarios were modeled in three Hazard Zones specified by the City. The first scenario modeled a benzene spill of 24,500 gallons in each of the three Hazard Zones. The second scenario simulated a benzene spill of 100,000 gallons in each zone. Aquifer hydraulic characteristics and a hypothetical soil type and thickness were chosen to represent each Hazard Zone. Hazard Zone I had 1.5 meters of Houston Black soil in the unsaturated zone and a saturated zone representative of an unfractured Edwards Aquifer that contains solution porosity. Hazard Zone II was not underlain by the Edwards. Hazard Zone III had 0.5 meters of the Brackett Soil Association in the unsaturated zone and a saturated zone representative of a highly fractured Edwards Aquifer that contains solution porosity.

The modelers used the U. S. Environmental Protection Agency’s Regulatory and Investigative Treatment Zone model (RITZ) (Nofziger et al., 1988) to model the transport of benzene in the vadose zone. Based on the mass loading calculated by RITZ, the U. S. Geological Survey Computer Model of Two-Dimensional Solute Transport (Konikow and Bredehoeft, 1978) was used to model dissolved phase movement of benzene in the saturated zone. This model consists of 400 nodes, and is homogeneous and isotropic (the model uses a constant thickness and hydraulic conductivity that does not vary with direction or location). The models are not calibrated and are generic in nature. That is, they do not attempt to model flow in the unsaturated or saturated zones based on known flow conditions.

Because of the inherent assumptions of the RITZ model, benzene could only be modeled as a dissolved "pollutant" that was leached out of the spill volume of pure benzene. Other assumptions of the model include: the "oil" is immobile and remains in the plow zone (shallow soils); flux of water is uniform through the treatment zone throughout time; slug flow (sharp front) prevails with no dispersion; linear isotherms describe the oil phase partitioning between liquid, soil, vapor, and oil phases; and first order degradation of the pollutant and oil is constant through time and soil depth.

This model would not be useful for the screening of a large volume pipeline spill overlying the Edwards Aquifer in the Barton Springs Segment. For the 24,500 gallon spill, the results for Hazard Zone III indicate that, for a soil 0.5 meters thick, 45% of the benzene volume would be degraded, 49% would be volatilized to the air, and 7% would reach the saturated zone (dissolved in water). These results are unlikely for several reasons. First, the RITZ model assumes that the oil phase never leaves the plow zone. In the field, a leak or rupture would be localized. Over such a thin soil, a large volume spill would probably not remain near the surface long enough for 49% to volatilize. Some of the separate phase volume would likely infiltrate deeper and possibly reach the water table. Also, the pipeline is buried deeper than 0.5 meters for much of its length across the Edwards Aquifer. The pipeline backfill is commonly disturbed native material and it would not have the same hydraulic properties as the native soil when replaced. The soil thickness assumption and the assumptions inherent in RITZ renders the vadose zone conceptual model to be not usable.

In the saturated zone, the inputs of 0.062 ft^2/sec transmissivity, a saturated thickness of 50 feet, and a hydraulic gradient of 5.68×10^{-3} were used for Zone III. The transmissivity value converts to a hydraulic conductivity of 107 feet per day. Multiplying by the hydraulic gradient, the advective Darcy velocity of the plume would be 0.61 feet per day. Inspection of the input file indicates that the porosity is 0.25. The average linear velocity (the Darcy velocity divided by the porosity) would be 2.43 feet/day.

The results of the USGS solute transport model run for the saturated zone revealed that the benzene plume traveled 750 feet in 12 months. Using the average linear velocity obtained above, the center of mass of the plume should travel 888 feet in 12 months. Although the agreement is good between the calculated travel distances, a numerical model was not required to obtain this result.

5.2.4 Slade et al. (1985)

Slade et al. (1985) constructed a two-dimensional, finite difference groundwater flow model of the Barton Springs Segment of the Edwards Aquifer. The U. S. Geological Survey code of Trescott, Pinder, and Larson (1976) was used to implement the model. The analysts used 318 active nodes in the finite difference grid, which was overlain on a map of the aquifer area. Grid spacing was made variable depending on the location. Cells in the eastern portion of the grid were made larger because the hydraulic gradient is smaller and the saturated thickness was estimated to be more uniform. The major limitation of this model is that it models the Edwards as being a porous medium.

An initial steady-state run was performed to obtain starting values for the model. Recharge to the model was set equal to the discharge (50 ft^3/sec) and was assigned to the cells occupying the area of the stream channels (85%) and to stream tributaries and outcrop areas (15%). The amount of recharge to each watershed was determined from information from flow-loss studies. Pumpage was determined by using the data from 1981 and distributing it evenly throughout the year. Hydraulic head data from 1981 were also used. Transmissivity was initially estimated from specific capacities, contoured, and input by overlaying the model grid. However, this was found to be inaccurate when an attempt was made to match known head levels. Transmissivities re-estimated by flow net analysis and adjustment of model cell widths were found to be adequate.

The steady-state model was then calibrated by adjusting the transmissivity values until the best match to the hydraulic head data was obtained. Anisotropic values of transmissivity were not found to improve the head match between simulated and measured values. Saturated thickness varied from 100 to 450 feet. The authors determined that the transmissivity of the aquifer increases with proximity to Barton Springs. Transmissivity in the calibrated model was also larger in the streambed locations. Further, it was found that water levels in the aquifer are interrelated and correlate with Barton Springs discharge. The range of transmissivity used in the model is between approximately 1000 and 1,000,000 ft^2/day.

Transient model simulations for the period August 8, 1979 to January 18, 1980 were also performed. Daily recharge and discharge data were used in the model. The purpose of this model was: 1) to adjust the values of specific yield and storativity until calibration to hydraulic head values was achieved, and 2) to verify the hydraulic conductivities from the steady state model. Increasing the specific yield tended to raise water levels in the model aquifer and increase the simulated discharge of Barton Springs. The mean specific yield determined from the modeling was 0.014 with a range of 0.008 to 0.064. The average transient model value of hydraulic conductivity in the outcrop region traversed by the pipeline is 6.0 feet/day. The average hydraulic conductivity is 174 feet/day in the area of the pipeline crossing where the Edwards is confined.

In general, the models were successful in simulating the overall shape of the potentiometric surface. Exact matches to measured water levels and spring flow rates were not obtained.

5.3 Tracer Study of Hauwert et al. (1998)

This preliminary report describes the results of groundwater tracer studies in the Barton Springs Segment of the Edwards Aquifer. Five tracer tests were performed in the Barton and Williamson Creek watersheds by the emplacement of liquid dye directly into known recharge features followed by flushing with fresh water. Injection points in sinkholes in creek beds were excavated to a depth of four to five feet and flushed with up to 9000 gallons of water. Tracer dye was also placed in one well and flushed with 200 gallons of water. Reception points were located at Barton Springs, Cold Springs, the Colorado River and several wells. Some of the wells were pumped after the injection.

Both water samples and charcoal detectors were used to test for the presence of the dye in groundwater. A trace was considered to be recovered if the concentration was at least ten times the background concentration and the tracer concentration was at least three times the detection limit for the type of receptor used. The results indicated that the contributing zone to Cold Springs was larger than previously known. The tracer studies also indicated that the velocities of the traces (based on the initial recovery time where the tracer concentration was at least three times the detection limit) ranged from 0.07 to 4 miles per day. Concentration peak recovery velocities ranged from 0.03 to 4.5 miles per day.

5.4 Groundwater Impacts to the Edwards Aquifer from a Pipeline Leak or Rupture

Rose (1986) performed an assessment of pipeline leak statistics for the period 1971-1985 for the Edwards Aquifer. On the average, 50 percent of spilled oil was recovered. It was estimated that a spill of 42,000 gallons or larger has a reasonable probability of reaching the water table in the unconfined Edwards. A spill of 210,000 gallons or greater was expected to result in groundwater contamination. Of the 15,000 reported spills during the study period, 3 percent were spills of 42,000 gallons or more. A spill of such a magnitude is expected once every 15 months on average.

The Barton Springs Segment of the Edwards Aquifer is the most sensitive aquifer crossed by the proposed pipeline. The existing pipeline route crosses Barton Creek in the contributing zone of the aquifer approximately 3000 feet east of the Cedar Valley Pump Station. This would be a sensitive area, because in the event of a leak, contaminants could be washed downstream into the recharge zone. In the recharge zone, the pipeline does not cross any of the recharge-contributing creeks. The most sensitive portion of the route is the outcrop at the location of the permeable Kirschberg Evaporite member of the Kainer Formation and the leached and collapsed members of the Person Formation beginning a short distance west of Brodie Lane and extending about one mile west. This is near the Brodie Lane Karst Area discussed below. Small et al., (1996) state that the aquifer is most vulnerable to contamination from the surface in the rapidly urbanizing area on the aquifer outcrop. They further state that contamination can result from spills or leakage of hazardous materials or from runoff. Although a pipeline leak or rupture would pose a serious threat of contamination to the aquifer, it would be a localized event. Urban runoff also poses a serious threat to water quality because it is ongoing over a long period of time. Certainly, if a significant rainfall occurred after a spill, contaminants would be more easily flushed into the saturated zone.

There is a significant amount of uncertainty regarding groundwater flow in any fractured aquifer. The Edwards Aquifer consists of fractured limestone and dolomite with faults, caverns and other solution features in the subsurface. The regional characteristics of the aquifer stated above do not preclude the possibility of rapid localized groundwater movement with unexpected linear direction. In the event of a spill this could result in unanticipated movement of contaminants.

Another issue is related to the lack of a well-developed soil layer on the outcrop of the Edwards Aquifer. Soils with a high fraction of organic carbon tend to sorb organic constituents and retard their movement in the unsaturated and saturated zones. Also, well-developed soils usually contain abundant native bacteria that consume the constituents in oil, diesel, and gasoline, converting them to CO_2 and water over time. The soil conditions on the Edwards outcrop are not favorable for natural biodegradation of spilled petroleum products.

The City of Austin has designated four areas as Sensitive Karst Areas. These are the Kretschmarr Ranch Karst Area, the Beck Ranch Karst Area, the Brodie Lane Karst Area, and the Slaughter Creek Karst area. These areas contain a high concentration of karst features. The existing pipeline passes within 100 yards of the Brodie Lane Karst Area, which is a designated park. A ground penetrating radar survey conducted in this location by LBG-Guyton and Associates shows near surface voids, which indicate karst features that may not be apparent on visual inspection. The survey only goes down to ten feet and does not provide details on the interconnection of such voids. One such karst feature was observed in the pipeline right of way during a field trip. The Brodie Lane Karst Area is very sensitive because runoff from an adjacent spill could conceivably enter the groundwater very quickly.

Slade et al. (1985) determined that the transmissivity of the aquifer increases with proximity to Barton Springs. This means that moving the pipeline to the south would be beneficial for preventing Barton Springs contamination. However, the majority of the groundwater produced from the Barton Springs Segment is from the southernmost portion. Therefore, moving the pipeline to the south has the drawback of possibly contaminating downgradient wells. The existing pipeline is primarily in the Slaughter Creek watershed, which contributes about 6% of the annual recharge to the aquifer. Moving the pipeline to the south would place it in the Bear and Little Bear Creek watershed, which contributes 14% of the annual recharge to the aquifer. This would place the pipeline in a portion of the recharge zone where recharge is more focused. The pipeline would directly cross Bear and Little Bear Creeks in the recharge zone making it the most sensitive portion of the pipeline route over the Edwards.

5.5 Modeling Groundwater Impacts to the Edwards Aquifer from a Pipeline Leak or Rupture

The tracer studies of Hauwert et al. (1998) provide a worst case analysis of groundwater flow times. This is because the tracers were injected directly into known recharge features that were excavated and flushed with fresh water in most cases. Therefore, the tracer study results would be directly applicable to a situation where a large storm flushes hydrocarbons from a pipeline spill and introduces free phase or dissolved contaminants in high concentration to the creeks in the recharge area. Peak flows would then scour the creekbeds and introduce contaminants into the recharge features. This scenario is extreme and probably would not occur. The tracer studies are important, however, because they give an indication of travel times from the creek beds, which is the main source of recharge to the Edwards. The tracer findings are more reliable than modeling results because the data represent actual measured information. Worst case velocities of 0.07 to 4 miles per day were reported for the initial detection (ppb range) of the tracer dye. This is applicable because for organic constituents of gasoline, concentrations in parts per billion would be of concern.

The model of Kuniansky and Holligan (1994) provides results for groundwater flow but does not include contaminant transport. The model could be used as a tool to delineate regional advective movement of dissolved contaminants in groundwater. It also would be useful in simulations to determine rates of advective discharge to rivers and creeks. The Kuniansky and Holligan model would not be an appropriate for use on a local scale (less than one or two miles for example) because of the coarseness of the model grid. The model could not be used to model free phase product movement, unsaturated flow, or dispersive and diffusive movement of dissolved organic constituents.

In the RMT/Jones and Neuse (1994) model, the vadose zone component contains assumptions that render it unusable to characterize an unsaturated zone impact by a pipeline leak. Also, the saturated zone component of this model is not appropriate for use in the event of a pipeline leak. The model is generic, not calibrated, and does not attempt to model the Edwards Aquifer by incorporating aquifer characteristics. The plume travel distance is small and unrealistic when compared to the travel distances and times determined by Barrett and Charbeneau (1996), Slade et al. (1985), and Hauwert et al. (1998). The calculated plume travel distance is based on one average transmissivity value that was used for the entire homogeneous and isotropic modeled area. Also, one thickness value, 50 feet, was assigned for the entire model area. The transmissivity should increase with proximity to Barton Springs and the thickness can vary between 100 and 450 feet according to Slade et al. (1985). With only 400 nodes, and with constant input values, this model does not provide any benefit over analytical calculations.

The model of Barrett and Charbeneau (1996) combines groundwater flow and transport of a conservative species. The model successfully predicted spring discharge and water levels during the recession period in the fall of 1989. However, predicted discharge typically exceeded the measured discharge in subsequent verification tests. The model is unconventional in that the results are averaged over the entire aquifer and do not provide head or concentration values at points other than the specified five cells. However for flow through the model, the results are within the range of those from the tracer studies of Hauwert et al. (1998). This model is simple enough to be used as a quick check for the possible arrival time of contaminants from a pipeline spill. As with the tracer studies of Hauwert et al. (1998) the major limitation is that direct introduction of contaminants in the creekbeds is assumed. There is no possibility of modeling the travel time of contaminants that might impact the aquifer from elsewhere other than the creekbeds.

The two-dimensional finite difference groundwater flow model of Slade et al. (1985) is implemented by the public domain code of Trescott, Pinder, and Larson (1976). This code is no longer widely used, however, because of the development of three-dimensional codes such as MODFLOW. Also, it would be difficult to obtain a version for use on a modern personal computer. In general, the models were successful in simulating the overall shape of the potentiometric surface. Exact matches to measured water levels and spring flow rates were not obtained. The model does provide for variable transmissivity in the outcrop and confined portions of the aquifer and does introduce realism by including the effects of varying recharge and pumpage. In this regard, the modeling results provide the only published estimates of transmissivity variation in the aquifer. The main assumption is that the Edwards can be modeled as an equivalent porous medium. Because of the coarseness of the grid, this model could not be used to model a spill on a local scale (less than one mile). Also, the model cannot simulate contaminant transport and could only be used to estimate rates of advective transport of a conservative tracer on a regional scale.

5.6 Estimates of Groundwater Flow Rates in the Edwards Aquifer (Barton Springs Segment)

A conservative approach for estimating contaminant transport velocities in groundwater is to assume that dissolved constituents move as conservative species that are not retarded or degraded in any way. Average groundwater flow rates can then be assumed to be the rate of contaminant transport. In the Edwards, the average groundwater flow rates can be very rapid.

Using Darcy's law, the average groundwater velocity v is estimated from the modeling results of Slade et al. (1985) as follows:

$v = Q/An = Ki/n$ = 1.02 to 174.0 feet/day = 372 feet/year to 63,510 feet/year (0.07 to 12 miles/year)

Where:

Q = volumetric flow rate
A = Area perpendicular to flow

n = Porosity ≈ specific yield = 1.4%

K = Hydraulic Conductivity = 6.0 feet/day average in pipeline crossing where Edwards is unconfined; 174 feet /day average in pipeline crossing where Edwards is confined.

i = Hydraulic Gradient ≈ 0.0024 to 0.014

It must be recognized that locally, groundwater flow rates could be much higher than the average because of fracturing or solutioning (particularly in the confined portion). The absolute worst case is the result that was derived using the tracer study of Hauwert et al. (1998). They determined that the velocities of the traces (based on the initial recovery time) ranged from 0.07 to 4 miles per day (26 to 1460 miles per year). It must be recalled that the tracers were introduced directly into known recharge features that were excavated prior to the tracer injection and then flushed with water. Therefore, these results may not be indicative of native aquifer conditions.

After calibration, the model of Barrett and Charbeneau was used to simulate the movement of a conservative tracer through the Edwards. A 50-cfs pulse of recharge was simulated in the Onion Creek cell. The pulse took 20 days to be detected in the Barton cell. This is equivalent to a velocity of 0.64 miles per day or 232 miles per year. A subsequent pulse of 129 mg/L of nitrogen took 65 days to be detected in the ppb range in the Barton cell. These are also worst case results because the model tracers were directly recharged.

Table 2 summarizes the various velocity results. Based on the results, it appears that groundwater flow rates as high as one mile per day are possible in the Barton Springs Segment of the Edwards.

Table 2. Estimates of Groundwater Velocity in the Barton Springs Segment of the Edwards Aquifer

Source	Edwards Groundwater Velocity	Conditions
Model of Slade et al. 1985	372 feet/year (0.07 miles/year)	Average linear velocity in pipeline crossing over unconfined outcrop
Model of Slade et al. 1985	63,510 feet/year (12 miles/year)	Average linear velocity in pipeline crossing over confined portion
Tracer study of Hauwert et al. (1998)	0.07 to 4 miles per day (26 to 1460 miles per year)	1st detection of tracers introduced into recharge features that were excavated and then flushed with water.
Model of Barrett and Charbeneau (1996)	0.64 miles per day (232 miles per year)	50-cfs pulse of recharge simulated in the Onion Creek cell was then detected in the Barton cell.
Model of Barrett and Charbeneau (1996)	0.20 miles per day (73 miles per year)	129 mg/L nitrogen pulse in the Onion Creek cell was detected in the Barton cell at ppb levels.

6.0 CARRIZO-WILCOX AQUIFER - HYDROGEOLOGY AND REVIEW OF EXISTING MODELS

6.1 Hydrogeology of the Carrizo-Wilcox Aquifer

The Carrizo-Wilcox Aquifer is comprised of unconsolidated to loosely consolidated sands derived from a large ancient delta complex. Cross bedding and channel complexes are commonly observed in the outcrop. The older Wilcox Group comprises, from oldest to youngest (west to east), the Hooper formation, the Simsboro Formation, and the Calvert Bluff Formation. The Wilcox thins southeastward and becomes indistinguishable from the Calvert Bluff and Hooper Formations south of the Colorado River.

The Carrizo Formation is more lithologically uniform and has more consistent hydraulic conductivities than the Wilcox Thorkildsen et al. (1989). The Carrizo Formation of the lower Claiborne group unconformably overlies the Wilcox Group. Carrizo sediments are also fluvial in origin. The Carrizo Sand is light to dark grey, fine to coarse-grained, loose, poorly sorted (well graded) and thickly bedded. Unlike the Wilcox Group, the Carrizo forms a massive continuous sheet of sand over the study area (Thorkildsen and Price, 1991). This means that sand predominates with only minor beds of clay. Cross bedding is evident in exposures of the Carrizo. Carbonaceous clay and silty clay partings occur in the upper part. Locally, iron staining is prevalent and some beds are highly cemented with iron. The formation is about 100 feet thick in the Bastrop County area (Barnes, 1974) and has a maximum thickness of 375 feet (Follet, 1970). The formation thickens to the southeast with the thickest portion found in central Fayette County (Thorkildsen and Price, 1991). The Carrizo dips to the southeast at about 140 feet per mile. Complex zones of faulting are present in Bastrop, Lee, and Fayette Counties. The faults extend downward into the Wilcox. Thorkildsen et al. (1989) state that the range of hydraulic conductivity values is similar to that reported for the Wilcox Group.

Within the study area, the Carrizo-Wilcox Aquifer is nearly full and takes a limited amount of recharge. Only a small portion, called the effective recharge, is not rejected by springs on the outcrop or by evapotranspiration. When hydraulic heads are higher than the water table, seepage from lakes and streams can also contribute to the recharge. On a regional basis and over geologic time, some interformational leakage probably contributes recharge to the Wilcox. Recharge from direct infiltration of precipitation is likely to be focused in surficial channel sand deposits where cleaner, coarser grained sands (i.e. more permeable) are present. These areas of presumed focused recharge have not been formally mapped. However, soil surveys and infrared imaging could conceivably provide the necessary information.

Water levels measured in wells completed in the different layers of the Carrizo-Wilcox Aquifer show minor differences on a regional basis (Thorkildsen and Price, 1991). Because of this water levels from all the layers were combined on one water level map for use in this and previous studies (Figure 9). Due to the lack of flowlines to the southeast in potentiometric surface maps, it was deduced by MacPherson (1986) that very little recharge entering the Wilcox Group actually travels downdip to the artesian section of the aquifer. Most of the flowlines show that groundwater flow paths are directed toward rivers and creeks. The potentiometric surface is largely topographically controlled. In the outcrop area of the Carrizo and the Wilcox Group, potentiometric highs are found along surface water drainage divides and potentiometric lows are coincident with rivers and creeks. This means that groundwater moves from areas near surface water divides and then discharges to the rivers and creeks. The hydraulic gradient is steeper near the drainage divides than it is near the rivers. From this it is inferred that groundwater enters the aquifer in the outcrop area and most is discharged to smaller streams before it reaches the major discharge areas near rivers. The Carrizo potentiometric surface was not mapped separately because of a lack of data.

Figure 9

Natural discharge from the aquifer is mainly to the Colorado River. Recharge to the aquifer is mainly by precipitation on the outcrop. Seepage from lakes and streams and interformational leakage also contribute to the recharge. Within the study area, the Carrizo-Wilcox Aquifer is nearly full and takes a limited amount of recharge. Only a small portion is not rejected by springs on the outcrop or by evapotranspiration. Recharge may be focused in more sand-rich outcrops, but no documentation of this is available. Based on computer simulations, (Thorkildsen and Others, 1989) the natural rate of effective recharge was estimated to average just over one inch per year within the study area (3% of the average annual rainfall. Additional computer simulations indicated that increased pumpage would induce interformational leakage from overlying beds and increase the effective recharge to 5% of the annual rainfall amount.

There is a general lack of recent aquifer hydraulic data in the Carrizo-Wilcox. The Wilcox Group hydraulic conductivities are highly variable because of the complex lithology. Hydraulic conductivities in the Wilcox Group are reported to be 20 to 60 feet per day where channel sands are present Thorkildsen et al. (1989). Lower values of approximately 3 to 7 feet per day are said to be appropriate for interchannel portions of the aquifer. Carrizo-Wilcox storativities are 0.00001 to 0.001 in the artesian portion and 0.05 to 0.3 in the water table areas. Follet (1970) compiled aquifer test results from the 1940's and 1950's for the Wilcox in Bastrop County. The transmissivity from nine wells ranged from 147 to 3877 ft^2/day. Hydraulic conductivities in the Wilcox Group ranged from 2.5 ft/day to 24 ft/day. The higher values are from six aquifer tests performed by Guyton (1942) at Camp Swift. The lower values are from wells having 100 feet or less of saturated thickness. One of these tests is probably from the Calvert Bluff. The aquifer tests reported in Guyton (1942) are from Simsboro wells. Storativities reported from Follet (1970) are from 0.0003 to 0.0006. Specific capacities from well tests were 1.5 to 20.2 gpm/ft with the lower values being from the low transmissivity wells. As of 1993 the specific capacities of Aqua Water Supply Corporation's Camp Swift Wells #1 and #3 were 6.8 and 24.3 respectively.

Water level measurements in properly spaced wells have remained relatively constant through time. Depth to groundwater is 30 to 50 feet in the outcrop areas. In the artesian portions the depth to the main water bearing zones, the Carrizo and the Simsboro Formations, is between 300 and 1100 feet below surface. High capacity wells should be spaced 1200 to 2000 feet apart and major well fields should be spaced at least miles apart. There is a great deal of speculation that interformational leakage may occur between the Wilcox and water bearing sands that overly it particularly as a result of development. Although this is possible, Kier and Larkin (1998) found no hard evidence to support it. This "enhanced recharge" is often cited as a justification for increased development. However, this reasoning is likely to be unfounded.

Water use in the study area including Bastrop and the surrounding areas is from groundwater. The most prolific water-bearing zone is the Simsboro Formation of the Wilcox Group and the Carrizo Formation. In 1985 an estimated total of 6354 acre feet of groundwater was pumped in Bastrop County. Of this total, 6098 acre feet were pumped from the Carrizo-Wilcox Aquifer. The groundwater in the Carrizo-Wilcox becomes more saline with depth as one proceeds downdip into the artesian portion. The only water quality problem occurs “erratically” when high iron concentrations are found in water bearing sands. The iron concentration can also vary vertically in different sand layers within a single well.

6.2 Review of Existing Carrizo-Wilcox Aquifer Models

6.2.1 Thorkildsen et al. (1989)

The goal of this modeling was to construct an aquifer model of the Carrizo-Wilcox within Bastrop and northern Fayette Counties. Portions of adjacent Lee and Caldwell Counties are included in the model to allow the incorporation of boundary conditions.

The U. S. Geological Survey model, MODFLOW (McDonald and Harbaugh, 1988), was used to construct the model. The model grid consisted of 660 cells (22 rows and 30 columns) to cover the Carrizo-Wilcox Aquifer in the study area. Nodal dimensions varied from 2 by 2 miles to 2 by 4 miles. With five layers, the total number of nodes equals 3,300. The model was aligned northeast and southwest along strike and southeast-northwest along dip. The southeast boundary of the model was assigned to be at a constant head. The northwest model boundary was assigned to be no flow. The northeast and southwest boundary nodes were made large enough to place this portion of the model outside the Colorado River Basin. In this way, the outer portions of the model would not affect the results in the interior of the model. The first (uppermost) layer of the model was assigned to be unconfined. The remaining four layers were allowed to be convertible between confined and unconfined. The MODFLOW river module was used to simulate the Colorado River. Cells in that region were assigned heads reflecting the elevation of the river. The drain module was used to simulate rejected recharge.

Structural data input to the model included the top and bottom elevation of each layer. Several cross sections were constructed through the model area. These were determined by the interpretation of electric logs. Hydraulic conductivity was assigned on the basis of depositional environment as determined from the logs. Shales and silty shales were assigned a value of 0.134 feet/day. Interchannel sands were given a value of between 3.34 and 6.68 feet/day. Channel area hydraulic conductivities were between 20 and 66.8 feet/day. Maps were made of the weighted average hydraulic conductivity of each layer.

All sediments younger than the Carrizo Sand are grouped into Layer One of the model. These sediments act as a leaky artesian aquifer according to the authors. Layers Two, Three, Four, and Five of the model represent the Carrizo Sand, the Calvert Bluff Formation, the Simsboro Formation, and the Hooper Formation, respectively. The authors classify the Carrizo-Wilcox Aquifer as a leaky artesian system.

The modeling was performed in three phases. The purpose of Phase 1 was to calibrate the model. The best match to existing head data was obtained using a ratio of vertical to horizontal hydraulic conductivity of between 0.001 and 0.0001. Higher ratios of between 0.01 and 0.001 were used near the Colorado River in layers 2 through 5.

Phase 2 was designed to incorporate the drain and river packages in the model to determine how much recharge enters and stays in the system. From this phase, it was determined that the annual effective recharge was between 3 and 4 percent of the annual rainfall or 33,000 acre-feet. The simulations indicate that the total recharge is 144,000 acre-feet. Of that amount 65,000 acre-feet were rejected or "spilled recharge" and 45,000 acre-feet flowed to the Colorado River. It was also determined in Phase 2 that the effective recharge increased significantly if large scale pumping was simulated. The effective recharge increased in the outcrop area because of reduced outflow to the Colorado River. The effective recharge also increased because of vertical infiltration from layer 1 overlying the Carrizo. Other computer simulations indicate that additional pumpage would induce interformational leakage from overlying beds and increase the effective recharge to 5% of the annual rainfall amount.

The purpose of Phase 3 was to simulate several pumping scenarios to determine the drawdown. The amount of pumpage was varied from 5,763 acre-feet in 1985 to 14,479 acre-feet in 2029. Drawdown was simulated at existing pumping centers. Maximum drawdowns were approximately 15 feet under several scenarios in which pumpage and rainfall conditions were varied.

The authors make some cautionary statements in the Summary, Conclusions, and Recommendations section. The authors state that the model was constructed to help study regional trends within the aquifer. It should not be applied to site-specific problems. They caution that, in the past, large capacity wells have been located too close to existing wells and well fields. This caused excessive water level declines and loss of pumping well capacity.

6.2.2 Dutton (1999)

Dutton (1999) used the U. S. Geological Survey code MODFLOW (McDonald and Harbaugh, 1988) to construct a three-dimensional finite difference model of the Carrizo-Wilcox Aquifer. The study included the area between the Brazos and the Colorado Rivers in Bastrop, Lee, and Milam Counties. The model was designed to be regional in scope with nodal spacing of one mile squared to 16 miles squared. The modeling objective was to assess the ability of the Carrizo-Wilcox Aquifer to sustain additional future pumpage needed for industrial, municipal, and power plant use. The model was composed of 15,540 nodes in five model layers. Structural elevation of the individual layers and heterogeneous values of hydraulic conductivity were included in the model input.

The vertical hydraulic conductivity was assumed to be 0.01 times the horizontal hydraulic conductivity. It was determined that the field test-derived horizontal hydraulic conductivity (2.6 to 59 ft/day) in the Carrizo had a greater variance than the Simsboro, the Calvert Bluff, or the Hooper formations. This is contrary to reports by Thorkildsen et al. (1989). In the portion of the model traversed by the pipeline, the Simsboro horizontal hydraulic conductivity ranged from 2.3 to 60 ft/day. The Carrizo hydraulic conductivity ranged from 11 to 600 ft/day in the same portion of the model.

Calibration consisted of a comparison of simulated heads with hydrographs for 45 water wells. Six different pumping scenarios were modeled. These included various pumping rate schedules and simulation times. Based on the simulations, the author estimated a recharge rate of 62,000 acre-feet per year to the Carrizo-Wilcox Aquifer. Of this amount, it was determined that 75% flows downdip to the confined portion of the aquifer. Drawdown of water levels in the confined portion can induce more recharge by decreasing the net discharge to rivers according to the author. It was determined that there are adequate quantities of water to supply current and projected needs through the year 2050. Maximum drawdown in the year 2050 was estimated to be 480 feet in the Simsboro and 105 feet in the Carrizo.

6.3 Groundwater Impacts to the Carrizo-Wilcox Aquifer from a Pipeline Leak or Rupture

The Carrizo-Wilcox Aquifer is less likely to be contaminated over a large extent by a pipeline spill than the karstic aquifers to the west. Flow in the aquifer is laminar and much slower than in hard rock aquifers such as the Barton Springs Segment of the Edwards. Also, approximately 30 feet of soil overly the water table. Depending on the volume of the spill, hydrocarbons may not reach the water table. Also, organic carbon in the soil will tend to sorb spilled hydrocarbons. Native bacteria will allow for natural biodegradation of most of the gasoline constituents. This process could be enhanced by the introduction of oxygen into the subsurface as part of remedial activities. Of the major gasoline constituents, dissolved MTBE will travel the fastest because of its high solubility, low retardation factor, and resistance to biodegradation.

One factor that is sensitive in the Carrizo-Wilcox is the aquifer's tendency to reject recharge. The aquifer is so "full" (water levels are high) that much of the water that is potential recharge is discharged to creeks. If a spill occurs near a waterway, and if a significant rainfall event has recently occurred, chances are good that either free phase or dissolved phase contaminants will be discharged to the surface water.

6.4 Modeling Groundwater Impacts to the Carrizo-Wilcox Aquifer from a Pipeline Leak or Rupture

The model of Thorkildsen et al. (1989) is regional in scale and could not be used to model a spill that would likely be on the scale of one mile or less. The nodal dimensions in the model varied from 2 by 2 miles to 2 by 4 miles. Therefore, there is insufficient resolution to provide for a local scale model. Models typically are regional in scope because detailed information on a local scale is not available. Also the model does not include contaminant transport. The model could be used to provide an assessment of advective contaminant movement based on regional groundwater flow directions and the effects of pumpage centers.

Dutton (1999) used the same simulation code as Thorkildsen et al. (1989). Therefore, the same limitations and conclusions regarding the model's applicability to a pipeline spill situation apply. Dutton's model is more recent, however, and does include updated pumpage records.

6.5 Estimates of Groundwater Flow Rates in the Carrizo-Wilcox Aquifer

A conservative approach for estimating contaminant transport velocities in groundwater is to assume that dissolved constituents move as conservative species that are not retarded or degraded in any way. Average groundwater flow rates can then be assumed to be the rate of contaminant transport.

From pumping tests compiled by Follet (1970) and of Guyton (1942), and using Darcy's law for the Wilcox Group, the average groundwater velocity v is estimated as follows:

$v = Q/An = Ki/n = 0.025$ ft/day to 0.24 ft/day $= 9.0$ to 88 feet/yr

Where:

Q = Volumetric groundwater flow rate

A = Area perpendicular to flow

n = Porosity $\approx$ specific yield = 30%

K = Hydraulic Conductivity = 2.5 ft/day to 24 feet/day

i = Hydraulic Gradient $\approx$ 0.003 in the Bastrop area

Using the hydraulic conductivity range for channel sands used by Thorkildsen et al. (1989) for the combined Carrizo-Wilcox Aquifer yields:

$v = Q/An = Ki/n = 0.2$ ft/day to 0.7 ft/day = 73.0 to 256.0 ft/year

Where:

n = Porosity ≈ specific yield = 30%

K = Hydraulic Conductivity = 20 to 66.8 feet/day in channel area sands

i = Hydraulic Gradient ≈ 0.003

Using the hydraulic conductivity range employed by Dutton (1999) in simulations of the Carrizo Aquifer yields

$v = Q/An = Ki/n = 0.1$ ft/day to 6.0 ft/day = 37.0 to 2190 ft/year

Where:

n = Porosity ≈ specific yield = 30%

K = Hydraulic Conductivity = 11 to 600 feet/day

i = Hydraulic Gradient ≈ 0.003

7.0 CONCLUSIONS

A review of groundwater modeling literature and an assessment of potential pipeline spill impacts for select aquifers along the Longhorn Pipeline route was performed. The aquifers studied were the Edwards-Trinity Aquifer, the Barton Springs Segment of the Edwards Aquifer, and the Carrizo-Wilcox Aquifer.

Several general conclusions were reached regarding the possible impact to groundwater of a pipeline spill:

- For all of the aquifers considered, there is no existing groundwater flow and contaminant transport model that is appropriate for use in characterizing a pipeline spill. Therefore, analytical modeling techniques employing the best available data would provide the most useful results in cases where estimates of groundwater contaminant transport are required. Two computer-implemented analytical models that could be applied to a spill scenario are documented and currently available: RITZ and HSSM.

- Based on the available information, the aquifers in order of highest to lowest contamination potential are the Barton Springs Segment of the Edwards Aquifer, the Edwards-Trinity Aquifer, and the Carrizo-Wilcox Aquifer. The most sensitive portions of the Barton Springs Segment of the Edwards Aquifer are the outcrops of the permeable Kirschberg Evaporite member of the Kainer Formation and the leached and collapsed members of the Person Formation. The existing pipeline passes within 100 yards of the Brodie Lane Karst Area. This area is very sensitive because runoff from an adjacent spill could enter the groundwater very quickly. The current pipeline route does not cross any of the contributing creekbeds in the recharge zone. The proposed southern route crosses Little Bear and Bear Creeks in the recharge zone. If approved, the creek crossing areas would be considered to be sensitive for a potential groundwater impact in the event of a leak.

- In the event of a spill, the introduction of petroleum products into the saturated zone would be enhanced because the pipeline will operate under pressure, and because it is buried along most of its length. Unconfined aquifers (particularly in areas of focused recharge) are more likely to be impacted from a pipeline spill than confined aquifers.

- The fact that the pipeline will transmit primarily gasoline instead of crude oil increases the potential for groundwater impacts from a leak or rupture. This is because gasoline consists of a larger fraction of constituents that are mobile when dissolved in groundwater when compared to crude oil. In particular, MTBE has the highest concentration in gasoline (for those gasolines containing this additive) and the highest mobility in groundwater. It must be recognized, however, that there is no maximum contaminant level for MTBE. It is undesirable in groundwater because of taste and odor. Benzene dissolved in groundwater is the main gasoline constituent of concern. Although benzene is less mobile than MTBE, it is a known human carcinogen. Gasoline constituents ethylbenzene, toluene, and xylenes are undesirable in groundwater because of possible liver, kidney and nervous system effects.

- Several studies have shown that hydrocarbon plumes reach a steady state and do not significantly expand after an initial period of spreading in shallow aquifers composed of interbedded sands, silts, and clays. The main hydrocarbon constituents from gasoline (benzene, toluene, ethylbenzene and xylenes) tend to move slower than the average rate when dissolved in groundwater. This is due to dispersion, dilution, sorption, and biogeochemical processes where native bacteria consume the hydrocarbons under aerobic and anaerobic conditions. Natural degradation of MTBE has not been completely documented in the literature, but it appears that some natural degradation occurs, albeit very slowly. MTBE dissolved in groundwater would be expected to move at the average groundwater flow rate with dilution and dispersion being the primary attenuation mechanisms with distance from a spill.

- Clastic aquifers consisting of unconsolidated sand, silt, and clay are less prone to widespread contamination from a possible pipeline spill than are karstic limestone aquifers. Tracking and remediating hydrocarbon plumes in karst aquifers such as the Edwards-Trinity and the Barton Springs Segment of the Edwards is more problematic than in shallow clastic aquifers. This is due to the unpredictable distribution of secondary (solution) porosity features in hard rock.

- The transmissivity of the Barton Springs Segment of the Edwards Aquifer increases with proximity to Barton Springs. In the event of a spill impacting groundwater, a more southern pipeline route would reduce the probability of Barton Springs contamination because dissolved hydrocarbons would be transported in slower moving groundwater. But because drinking water supply wells are concentrated there, moving the pipeline to the south has the drawback of possibly contaminating drinking water supply wells downgradient of the pipeline in the event of a spill. The existing pipeline is primarily in the Slaughter Creek watershed, which contributes about 6% of the annual recharge to the aquifer. Moving the pipeline to the south would place it in the Bear and Little Bear Creek watershed, which contributes 14% of the annual recharge to the aquifer. Therefore, moving the pipeline to the south also has the drawback of placing it in an area of more concentrated recharge. The pipeline would directly cross Bear and Little Bear Creeks in the recharge zone making it the most sensitive portion of the pipeline route over the Edwards.

- Plume movement from a pipeline spill can be estimated using the groundwater average linear velocity. To accomplish this, dissolved contaminants are estimated to move at the average linear groundwater velocity. Further, it is assumed that contaminants dissolve in groundwater immediately following a spill and are not retarded or degraded. It should be understood that these are average estimates. Dissolved constituents could move faster or slower than the average rate.

-- Edwards-Trinity Aquifer - Groundwater flow rates could range from 10 to 1230 feet per year. Dissolved contaminants such as MTBE and BTEX compounds could migrate 10 to 1230 feet in one year following a spill.

-- Edwards Aquifer Barton Springs Segment - From tracer studies, groundwater flow rates could range from 0.07 to 4.0 miles per day. Dissolved contaminants such as MTBE and BTEX compounds could migrate 0.07 to 4.0 miles in one day following a spill.

-- Carrizo-Wilcox Aquifer - Groundwater flow rates could range from 10 to 2200 feet per year. Dissolved contaminants such as MTBE could migrate 10 to 2200 feet in one year following a spill. BTEX compounds could move at these rates but would be likely to move slower.

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